

Pair production of quarkonia and electroweak bosons from double-parton scatterings in nuclear collisions at the LHC

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Abstract

Cross sections for the concurrent production of pairs of quarkonia ($J/\psi, \Upsilon$) and/or W,Z gauge bosons from double-parton scatterings (DPS) in high-energy proton-nucleus and nucleus-nucleus collisions at the LHC are calculated. The estimates are based on next-to-leading-order perturbative QCD predictions, including nuclear modifications of the parton densities, for the corresponding single-scattering cross sections. Expected event rates for $J/\psi + J/\psi$, $J/\psi + \Upsilon$, $J/\psi + W$, $J/\psi + Z$, $\Upsilon + \Upsilon$, $\Upsilon + W$, $\Upsilon + Z$, and same-sign W+W production in their (di)leptonic decay modes, after typical acceptance and efficiency losses, are given for p-Pb and Pb-Pb collisions.

1. Introduction

Particle production in high-energy hadron-hadron collisions is dominated by multiple interactions of their constituent partons. At LHC energies, most of the quarks and gluons forming the colliding protons and nuclei interact at semi-hard scales $O(1 - 3 \text{ GeV})$ and fragment into “minijet” bunches of final-state hadrons. About half of the particles produced in a standard proton-proton (p-p), proton-nucleus (p-A), and nucleus-nucleus (A-A) collision at the LHC come from the radiation and fragmentation of such secondary partonic interactions (the other half coming from the hardest parton-parton scattering in the event, and/or from softer “peripheral” interactions). Many basic event properties –such as the distributions of hadron multiplicities in “minimum bias” collisions as well as the underlying event activity in hard scattering interactions– can only be explained by taking into account hadron production issuing from such multiparton interactions (MPIs) occurring in each single p-p, p-A, and A-A collision [1, 2]. Monte Carlo (MC) generators reproduce all such properties by modeling the colliding hadrons through longitudinal parton distribution functions (PDFs) complemented with a parametrisation of their transverse parton profile as a function of impact-parameter (**b**).

The existence of MPIs at semi-hard scales naturally supports the possibility of double-parton scatterings (DPS) producing, in the same collision, two independently-identified particles at *harder* scales, $O(3 - 100 \text{ GeV})$. Various differential distributions in W+jets [3, 4] and $J/\psi + W$ [5] processes in p-p at the LHC show excesses of events –above the expectations from single-parton scatterings (SPS) alone– consistent with DPS contributions. There are, however, still large uncertainties on the DPS extraction due to (i) the contributions of higher-order SPS processes, (ii) our limited knowledge of the proton transverse parton profile [6] and its energy evolution, and (iii) the role of multi-parton correlations in the hadronic wave functions [7]. In Refs. [8, 9], we have highlighted the importance of studying DPS in p-A and A-A collisions as a complementary means to clarify such open issues.

In a generic (model-independent) way, one can write the DPS cross section simply as the product of the SPS cross sections, σ^{SPS} , normalised by an effective cross section $\sigma_{\text{eff,pp}}$ characterising the transverse area of the hard partonic interactions i.e., in the case of p-p collisions,

$$\sigma_{(pp \rightarrow ab)}^{\text{DPS}} = \left(\frac{m}{2}\right) \frac{\sigma_{(pp \rightarrow a)}^{\text{SPS}} \cdot \sigma_{(pp \rightarrow b)}^{\text{SPS}}}{\sigma_{\text{eff,pp}}}, \quad (1)$$

where σ^{SPS} is computable perturbatively, at a given order of accuracy in α_s , through convolution of the partonic subprocess cross sections and the proton PDFs, and $(m/2)$ is a combinatorial factor accounting for (in)distinguishable $m = 2$ ($m = 1$) final-states. A numerical value $\sigma_{\text{eff,pp}} \approx 15$ mb has been obtained from empirical fits to DPS-sensitive distributions in p-p at the LHC [3, 4]. One can identify $\sigma_{\text{eff,pp}}$ with the inverse of the proton overlap-function squared: $\sigma_{\text{eff,pp}} = \left[\int d^2b t^2(\mathbf{b})\right]^{-1}$, under the two following assumptions: (i) the (generalised) proton PDFs can be decomposed into longitudinal and transverse components, with the latter expressed in terms of the overlap function $t(\mathbf{b}) = \int f(\mathbf{b}_1)f(\mathbf{b}_1 - \mathbf{b})d^2b_1$ for a given parton transverse thickness function $f(\mathbf{b})$, and (ii) the longitudinal component reduces to the “diagonal” product of two independent single PDFs. Explaining the fact that the measured $\sigma_{\text{eff,pp}}$ is about a factor of two smaller than estimates based on naive geometric parametrisations of the proton profile [10], and ascertaining the evolution of $\sigma_{\text{eff,pp}}$ with collision energy, remain two important open issues in DPS studies.

In p-A collisions, the SPS cross section is simply that of proton-nucleon (p-N) collisions –taking into account possible modifications of the nuclear PDFs compared to the free nucleon– scaled by the number of nucleons (A) in the nucleus [11]. The DPS cross sections are further enhanced due to interactions where the two partons of the nucleus belong either to the same nucleon or to two different nucleons [12]. The corresponding “pocket formula” reads [8]:

$$\sigma_{pA \rightarrow ab}^{\text{DPS}} = \left(\frac{m}{2}\right) \frac{\sigma_{pN \rightarrow a}^{\text{SPS}} \cdot \sigma_{pN \rightarrow b}^{\text{SPS}}}{\sigma_{\text{eff,pA}}}, \text{ with } \sigma_{\text{eff,pA}} = \frac{\sigma_{\text{eff,pp}}}{A + \sigma_{\text{eff,pp}} F_{pA}} \approx 22.6 \mu\text{b}, \quad (2)$$

with $F_{pA} = \frac{A-1}{A} \int T_{pA}^2(\mathbf{r}) d^2r$, where $T_{pA}(\mathbf{r})$ is the standard Glauber nuclear thickness function [11], and the last numerical equality holds for p-Pb using $A = 208$, $\sigma_{\text{eff,pp}} = 15$ mb, and $F_{pA} = 30.4 \text{ mb}^{-1}$. The DPS cross sections in p-Pb are thus enhanced by a factor of $\sigma_{\text{eff,pp}}/\sigma_{\text{eff,pA}} \approx 3A \approx 600$ compared to p-p. Since the parameter F_{pA} depends on the (comparatively better) known transverse density profile of nuclei, one can exploit such a large DPS signal in p-A collisions to determine the value of $\sigma_{\text{eff,pp}}$ independently of p-p measurements.

In the A-A case, the single-parton cross section is that of p-p (again, modulo nuclear PDF modifications) scaled by A^2 , and the DPS cross section is further enhanced due to contributions coming from interactions where the two partons belong or not to the same pair of nucleons of the colliding nuclei [9]:

$$\sigma_{(AA \rightarrow ab)}^{\text{DPS}} = \left(\frac{m}{2}\right) \frac{\sigma_{(NN \rightarrow a)}^{\text{SPS}} \cdot \sigma_{(NN \rightarrow b)}^{\text{SPS}}}{\sigma_{\text{eff,AA}}}, \text{ with } \sigma_{\text{eff,AA}} = \frac{1}{A^2 \left[\sigma_{\text{eff,pp}}^{-1} + \frac{2}{A} T_{AA}(0) + \frac{1}{2} T_{AA}(0) \right]} \approx 1.5 \text{ nb}. \quad (3)$$

Here $T_{AA}(\mathbf{b})$ is the nuclear overlap function [11] and the last equality holds for Pb-Pb ($T_{AA}(0) = 30.4 \text{ mb}^{-1}$). The three terms in the denominator indicate the three DPS contributions from interactions where: (i) the two colliding partons belong to the same pair of nucleons, (ii) partons from one nucleon in one nucleus collide with partons from two different nucleons in the other nucleus, and (iii) the two colliding partons belong to two different nucleons from both nuclei. Their relative contributions are approximately 1:4:200, with the last (Glauber binary scaling) term clearly dominating. Whereas the single-parton cross sections in Pb-Pb are enhanced by a factor of $A^2 \approx 4 \cdot 10^4$ compared to that in p-p, the corresponding double-parton cross sections are boosted by a much larger factor of $\sigma_{\text{eff,pp}}/\sigma_{\text{eff,AA}} \propto A^{3.3}/5 \approx 9 \cdot 10^6$. Pair-production of pQCD probes issuing from DPS represents thus an important feature of heavy-ion collisions at the LHC and needs to be taken into account in any attempt to interpret the event-by-event characteristics of any observed suppression and/or enhancement of their yields in Pb-Pb compared to p-p data.

2. Production of $J/\psi J/\psi$ in Pb-Pb at 5.5 TeV and $W^\pm W^\pm$ in p-Pb at 8.8 TeV via double parton scatterings

The DPS cross section for double- J/ψ production in Pb-Pb has been computed with Eq. (3) using the colour evaporation model (CEM) NLO predictions [13] for the SPS J/ψ cross section, which reproduce well the experimental data (squares in Fig. 1 left), including EPS09 nuclear PDFs [14]. The two top curves in Fig. 1 (left) show the single- J/ψ (dashes) and double- J/ψ (dots) cross sections in Pb-Pb versus nucleon-nucleon c.m. energy $\sqrt{s_{NN}}$. Their ratio is shown in the bottom panel. At the nominal Pb-Pb energy of 5.5 TeV, the single prompt- J/ψ cross sections is ~ 1 b, and $\sim 20\%$ of such collisions are accompanied by the production of a second J/ψ from a double parton interaction. The probability of J/ψ - J/ψ DPS production increases rapidly with decreasing impact-parameter and $\sim 35\%$ of the the most central Pb-Pb $\rightarrow J/\psi + X$ collisions have a second J/ψ in the final state [9]. Accounting for dilepton decays, acceptance and efficiency –which result in a $\sim 3 \cdot 10^{-7}$ reduction factor in the ATLAS/CMS (central) and ALICE (forward) rapidities– the visible cross section is $d\sigma_{J/\psi J/\psi}^{\text{DPS}}/dy|_{y=0,2} \approx 60$ nb, i.e. about 250 double- J/ψ events per unit-rapidity in the four combinations of dielectron and dimuon channels for a $\mathcal{L}_{\text{int}} = 1 \text{ nb}^{-1}$ integrated luminosity, assuming no net in-medium J/ψ suppression/enhancement. These results show quantitatively that the observation of a J/ψ pair in a given Pb-Pb event should not be (blindly) interpreted as indicative of J/ψ production via $c\bar{c}$ regeneration in the quark-gluon-plasma [15], since DPS constitute an important component of the total J/ψ yield with or without final-state dense medium effects.

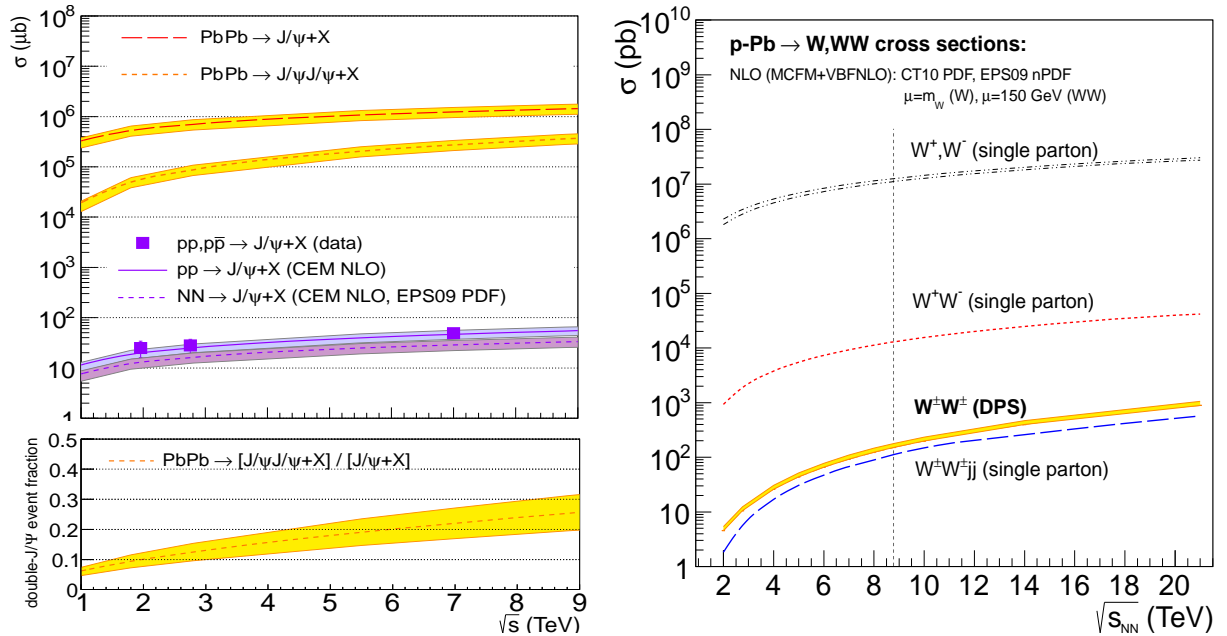


Figure 1. Cross sections as a function of c.m. energy for: (i) prompt- J/ψ production in p-p, N-N, and Pb-Pb collisions and for double-parton $J/\psi J/\psi$ in Pb-Pb [9] (left); and (ii) single-W and W-pair boson(s) from single-parton and double-parton scatterings in p-Pb (right) [8].

Same-sign WW production –whose theoretical cross section has small uncertainties and its experimental signature is characterised by a “clean” final-state with like-sign leptons plus large missing transverse energy from the undetected neutrinos– has no SPS backgrounds at the same order in α_s , and has been proposed since long as a “smoking gun” of DPS in p-p collisions [16]. We have computed the DPS cross section in p-Pb via Eq. (2) using mCFM 6.2 [17] at NLO accuracy for the single-parton W cross section, with CT10 proton [18] and EPS09 nuclear [14] PDFs and theoretical scales $\mu = \mu_F = \mu_R = m_W$. Figure 1 (right) shows the total cross sections for all relevant processes in the range $\sqrt{s_{NN}} \approx 2$ –20 TeV. At the nominal 8.8 TeV, the same-sign WW DPS cross section is $\sigma_{pPb \rightarrow WW}^{\text{DPS}} \approx 150$ pb (yellow thick curve), i.e. a factor of 1.5 times higher than the SPS background, $\sigma_{pPb \rightarrow WW jj}^{\text{SPS}}$, obtained adding the QCD and electroweak cross sections for the production of $W^+ W^+$ ($W^- W^-$) plus 2 jets pairs (lowest dashed curve). Accounting for the leptonic decay ratios and applying standard ATLAS/CMS acceptance and reconstruction cuts, one expects about 10 DPS same-sign WW events in 2 pb^{-1} integrated luminosity [8].

3. Pair production of quarkonia and vector bosons in double-parton scatterings in p-Pb and Pb-Pb

Table 1 collects the DPS cross sections for quarkonium and electroweak-boson pair production in p-Pb and Pb-Pb collisions at the LHC obtained via Eqs. (2) and (3) respectively. The corresponding NLO SPS cross sections (computed with CEM for $J/\psi, \Upsilon$; and mCFM for W, Z) are: (i) $\sigma_{NN \rightarrow J/\psi}^{\text{SPS}} = 25 \mu\text{b}$, $\sigma_{NN \rightarrow \Upsilon}^{\text{SPS}} = 1.7 \mu\text{b}$, $\sigma_{NN \rightarrow W}^{\text{SPS}} = 30 \text{ nb}$, $\sigma_{NN \rightarrow Z}^{\text{SPS}} = 20 \text{ nb}$ at 5.5 TeV; and (ii) $\sigma_{pN \rightarrow J/\psi}^{\text{SPS}} = 45 \mu\text{b}$, $\sigma_{pN \rightarrow \Upsilon}^{\text{SPS}} = 2.6 \mu\text{b}$, $\sigma_{pN \rightarrow W}^{\text{SPS}} = 60 \text{ nb}$, and $\sigma_{pN \rightarrow Z}^{\text{SPS}} = 35 \text{ nb}$ at 8.8 TeV. The visible DPS yields for $\mathcal{L}_{\text{int}} = 1 \text{ pb}^{-1}$ and 1 nb^{-1} , are obtained taking into account: $\text{BR}(J/\psi, \Upsilon, W, Z) = 6\%, 2.5\%, 11\%, 3.4\%$ per (di)lepton decay; plus simplified acceptance and efficiency losses: $\mathcal{A} \times \mathcal{E}(J/\psi) \approx 0.01$ (over $|y| = 0, 2$), and $\mathcal{A} \times \mathcal{E}(\Upsilon; W, Z) \approx 0.2, 0.5$ (over $|y| < 2.5$). All listed processes are in principle observable in the LHC heavy-ion runs. Other DPS processes like $W+Z$ and $Z+Z$ have much lower visible cross sections and are not quoted.

System		$J/\psi + J/\psi$	$J/\psi + \Upsilon$	$J/\psi + W$	$J/\psi + Z$	$\Upsilon + \Upsilon$	$\Upsilon + W$	$\Upsilon + Z$	ss WW
Pb-Pb	σ^{DPS}	210 mb	28 mb	500 μb	330 μb	960 μb	34 μb	23 μb	630 nb
5.5 TeV	$\text{N}^{\text{DPS}} (1 \text{ nb}^{-1})$	~ 250	~ 340	~ 65	~ 14	~ 95	~ 35	~ 8	~ 15
p-Pb	σ^{DPS}	45 μb	5.2 μb	120 nb	70 nb	150 nb	7 nb	4 nb	150 pb
8.8 TeV	$\text{N}^{\text{DPS}} (1 \text{ pb}^{-1})$	~ 65	~ 60	~ 15	~ 3	~ 15	~ 8	~ 1.5	~ 4

Table 1. DPS production cross sections of double- J/ψ , $J/\psi + \Upsilon$, $J/\psi + W$, $J/\psi + Z$, double- Υ , $\Upsilon + W$, $\Upsilon + Z$, and same-sign WW in Pb-Pb and p-Pb at the LHC. The corresponding DPS yields, after (di)lepton decays and acceptance+efficiency losses, are given for 1 nb^{-1} and 1 pb^{-1} respectively.

4. Summary

Multiparton interactions are a major contributor to particle production in hadronic collisions at high energy. The large transverse parton density in nuclei results in a high probability of having two truly hard scatterings in p-A and A-A collisions. The cross sections for the simultaneous production of quarkonia and/or electroweak bosons from DPS processes in nuclear collisions at the LHC, have been computed using NLO predictions for the corresponding single-parton cross sections. Processes such as double- J/ψ , $J/\psi \Upsilon$, $J/\psi W$, $J/\psi Z$, double- Υ , ΥW , ΥZ , and same-sign WW production have large cross sections and visible event rates for the nominal LHC luminosities. The study of such processes in p-Pb can help determine the effective σ_{eff} parameter characterising the transverse parton distribution in the nucleon. Double- J/ψ and double- Υ production in Pb-Pb provide interesting insights on the event-by-event dynamics of quarkonia in hot and dense strongly-interacting matter.

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